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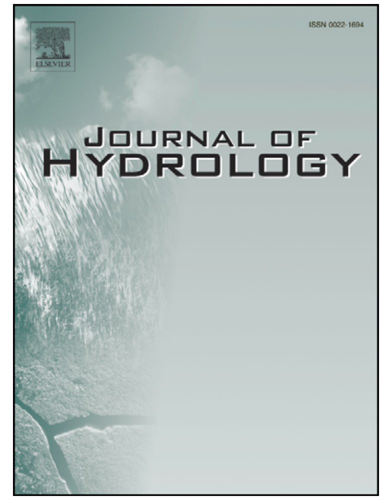

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Developing an integrated hydrograph separation and lumped modelling approach to quantifying hydrological pathways in Irish river catchments

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Non-Standard Abbreviations.[1]

Abstract

An appreciation of the quantity of streamflow derived from the main hydrological pathways involved in transporting diffuse contaminants is critical when addressing a wide range of water resource management issues. In order to assess hydrological pathway contributions to streams, it is necessary to provide feasible upper and lower bounds for flows in each pathway. An important first step in this process is to provide reliable estimates of the slower responding groundwater pathways and subsequently the quicker overland and interflow pathways. This paper investigates the effectiveness of a multi-faceted approach applying different hydrograph separation techniques, supplemented by lumped hydrological modelling, for calculating the Baseflow Index (BFI), for the development of an integrated approach to hydrograph separation. A semi-distributed, lumped and deterministic rainfall runoff model known as NAM has been applied to ten catchments (ranging from 5 to 699 km^2). While this modelling approach is useful as a validation method, NAM itself is also an important tool for investigation. These separation techniques provide a large variation in BFI, a difference of 0.741 predicted for BFI in a catchment with the less reliable fixed and sliding interval methods and local minima turning point methods included. This variation is reduced to 0.167 with these methods omitted. The Boughton and Eckhardt algorithms, while quite subjective in their use, provide quick and easily implemented approaches for obtaining physically realistic hydrograph separations. It is observed that while the different separation techniques give varying BFI values for each of the catchments, a recharge coefficient approach developed in

[1] NAM - Nedbør-Afstrømnings-Model", Danish software literally meaning rainfall runoff model.

Ireland, when applied in conjunction with the Master recession Curve Tabulation method, predict estimates in agreement with those obtained using the NAM model, and these estimates are also consistent with the study catchments' geology. These two separation methods, in conjunction with the NAM model, were selected to form an integrated approach to assessing BFI in catchments.

Keywords: river hydrograph separation; catchment modelling; recharge coefficients

1 Introduction

Understanding of the relative contributions of surface water and groundwater pathways underlies the objective of most catchment studies, whether the aims of the study are flood prediction, power generation, ecosystem preservation and remediation, water resource management or contaminant transport. This has been the subject of many studies from over 70 years ago (Boussinesq, 1877; Horton, 1933) through the second half of the 20th century (Pinder and Jones, 1969; Sklash and Farvolden, 1979; Nathan and McMahon, 1990; Chapman and Maxwell, 1996) up to recent times (Sivapalan et al., 2003; Brodie and Hostetler, 2005; Eckhardt, 2008; Santhi et al., 2008). Research has focused on simple separation approaches that relied heavily on the analyst's experience, such as graphical separation techniques, (Linsley, 1958; Linsley Jr et al., 1975; Frohlich et al., 1994; Szilagyi and Parlange, 1998) and on less subjective means of separation such as filtering algorithms like the local minima turning point separation method (Institute of Hydrology, 1980), the fixed and sliding interval methods (Pettyjohn and Henning, 1979), the Lyne and Hollick one-parameter algorithm (Lyne and Hollick, 1979), the Boughton-(Boughton, 1993) and the Eckhardt- (Eckhardt, 2005) two-parameter algorithms and the three parameter IHACRES filter (Jakeman and Hornberger, 1993). Analysis of the hydrographs recession following a rainfall event has also attracted much investigation to interpret the discharge processes dominating. Many approaches have been taken to elucidate the linear (Barnes, 1939; Tallaksen, 1995) and non-linear effects present (Coutagne, 1948; Van de Griend et al., 2002) based on the analysis by Boussinesq (1877) , that was applied to river discharge data (Maillet, 1905; Horton, 1933). The relationship between recharge of effective rainfall (rainfall less evapotranspiration) can further provide an indication of the groundwater, and conversely the quick responding pathways, will contribute to the river hydrograph. This has been investigated internationally (Rorabaugh, 1964; Rutledge and Survey, 1998; Scanlon et al., 2002) and in the Irish setting (Misstear and Fitzsimons, 2007; Misstear et al., 2009). These studies all sought to further understand the origin of the water and the processes that sustain a river's flow, which still drives much of the research and legislation internationally today (Dunn et al., 2010; Gomi et al., 2010; Dahlke et al., 2011; Ockenden and Chappell, 2011). The Water Framework Directive (WFD, 2000) is considered one of the most comprehensive pieces of European Union (EU) water legislation written to date. In contrast to previous EU directives, the WFD takes an integrated view of the water cycle and its components. It is now recognised that an understanding of the hydrological processes involved in a catchment is vital to predicting environmental and ecological impacts resulting from changes in land use and management practices. This requires the identification of the important pathways transporting both diffuse and point source contaminants to rivers and aquatic ecosystems.

Ireland's hydrogeological setting is an important driver of these hydrological processes and is dominated by fracture flow within the bedrock aquifers. These aquifers range from poorly productive aquifers, capable of transmitting only small amounts to water through the fractured-bedrock pathways, to regional important aquifers that have the capacity to transmit larger volumes of water. The classification is based on criteria such as aquifer areal extent, transmissivity, potential well yields, etc as explain by Geological Survey of Ireland (2006). The different classifications of aquifers are outlined in Table 1.

Table 1

The permeability, depth and slope of the overlying subsoils and soils will affect the quicker responding surface pathways. Conceptually, the main flow pathways contributing to rivers in an Irish setting are: overland flow, interflow, shallow groundwater flow and deep groundwater flow, as shown on Figure 1. Overland flow is rainfall runoff over the land's surface and into the first few millimetres of soil. It is conceptualised as occurring when the soil becomes saturated, i.e. saturation excess overland flow, typical of many catchments in temperate climates (Bonell, 1993). Interflow is conceptualised as lateral subsurface flow in soils and subsoils and can occur under both saturated and unsaturated conditions. Shallow groundwater is the groundwater component that occurs in the more transmissive upper part of the fractured-bedrock aquifer, where there is generally greater weathering of the rock and often greater numbers of open fractures than at depth. Finally, deep groundwater is defined as the groundwater in the main body of the less transmissive aquifer below this upper weathered layer. All four pathways are conceptualised as potentially contributing to streamflow.

Figure 1

The aims of the research project (the *Pathways* project) are to achieve a better understanding of these hydrological pathways, the fate and transport of waterborne contaminants, and the subsequent impact of these contaminants on aquatic ecosystems in Irish catchments. The contaminants being investigated include phosphorus, nitrogen, sediments, pesticides and pathogens. The project is to develop a Catchment Management Tool (CMT) to assist the Irish Environmental Protection Agency and River Basin District managers in achieving the objectives of the WFD. As an important element of this research is to quantify the proportion of the river hydrograph that is derived from each of the main pathways, a reliable approach is required to identify the overland and subsurface pathways.

The first step of this process is to calculate the contribution of the groundwater pathways contributing to the hydrograph, regarded as the baseflow or contribution of both shallow and deep groundwater. When separating baseflow from the observed discharge, certain qualitative rules have been applied to aid in assessing separations. These rules of thumb allowed the investigator to ascertain if the results of techniques applied are realistic or act as guidance in graphical separations carried out by hand on available hydrographs. The Australian Rainfall and Runoff report on Baseflow for Catchment Simulation (Merz et al., 2009) summarises five such rules concisely as:

1. Low flow conditions prior to the commencement of a flood event consist entirely of baseflow.
2. The rapid increase in river level relative to the surrounding groundwater level results in an increase in bank storage. The delayed return of this storage to the river causes the baseflow recession to continue after the peak of the total hydrograph.
3. Baseflow will peak after the hydrograph due to the storage-routing effect of the sub-surface stores.
4. The baseflow recession will most likely follow an exponential decay function.
5. The baseflow hydrograph will rejoin the total hydrograph as quickflow ceases.

These five assumptions of baseflow separation were employed when assessing the techniques employed in the catchments.

2 Study Catchments

In Ireland, the major land use is grassland, which covers approximately two-thirds of the total land area - and over 90% of all agricultural land (Brogan et al., 2002). Brown earths and Brown Podzolic type soils are common in the midlands and south, while gleyed soils are more common in the north and west. Subsoils consist of glacial deposits, mainly tills, together with peat, lascustrine deposits and alluvium (Archbold et al., 2009). The geological conditions of Ireland are highly heterogeneous across the country, with variations in subsoil and bedrock properties occuring over short distances. Examining the aquifer mapping available, approximately 73.5% of aquifers are poorly productive (Pl, Pu or Ll), with the more productive karst aquifers generally occurring in the west of the country. Most of the eastern half of the country receives between 750 and 1000 mm of rainfall in the year. Rainfall in the west generally averages between 1000 and 1400 mm. In many mountainous districts rainfall exceeds 2000 mm per year. Hail and snow contribute relatively little to the precipitation measured. The average annual potential evapotranspiration (PE) for the period 1971-2000 is between 440 and 552 mm for inland and maritime stations, respectively (Collins et al., 2004). Daily streamflow data are available from hydrometric stations maintained by the Office of Public Works (OPW) and the Environmental Protection Agency (EPA), with higher temporal resolution data available from a selection of these upon request. Three catchments were chosen from these sources, Deel, Blackwater (Kells) and Blackwater Fyanstown catchments, covering a range of different hydrological conditions. Supplementing these were three catchments in the Slieve Aughty mountains located on the Galway, Clare border. Three catchments were then used from the Pathways Project, Mattock (Louth, Meath), Nuenna (Kilkenny) and Glen Burn (Down). In these three catchments, data was obtained from four gauging stations that were specifically set up for this project. These supplementary catchments all had discharge data at one hour intervals or less. The catchment locations are shown in Figure 2, while Table 2 outlines the characteristics of these catchments.

Figure 2

Table 2

3 Methods

In order to quantify the contribution of the pathways, different techniques can be applied to calculate the BFI. These techniques range from studying the characteristics of recessions, using signal analysis methods, assessing geology, soil and subsoil cover, to implementing numerical models. Recession analysis, recursive digital filtering techniques, automated fixed and sliding interval approach, local minima turning point technique, recharge coefficient approach and lumped numerical modelling were used to constrain the quick responding flow from the baseflow and, where possible, the four pathways of the conceptual model, as described in the following sections.

3.1 Recession Analysis

A recession period is the time following a rainfall event during which stream discharge recedes until subsequent rainfall increases discharge once more. It has been observed in many studies that the recession of the hydrograph can be approximated with a linear reservoir (Horton, 1933; Nathan and McMahon, 1990; Chapman, 1999; Brodie and Hostetler, 2005). Discharge from a linear reservoir, with no recharge occurring over the period, can be expressed as:

$$Q_t = Q_0 e^{-t/\tau} = Q_0 k^t \qquad (1)$$

where Q_t and Q_0 are the discharge at times t and start of the recession, time 0, and τ is the response or turnover time of the reservoir. The term $e^{-(1/\tau)}$ is usually termed the recession constant k and used to inform automated signal filtering techniques. This equation is obtained from the solution to the water continuity equation:

$$Q = -\frac{dS}{dt} \qquad (2)$$

where S is the storage of the reservoir [L^3], using the linear relationship of discharge to storage:

$$Q_t = \frac{S_t}{\tau} \qquad (3)$$

The general suitability of the assumption of the groundwater storage being a linear reservoir has been questioned as many recessions do not always form a straight line on a semi-logarithm plot (Barnes, 1939; Chapman, 1999; Fenicia et al., 2006). However, it has been demonstrated that although simplistic in its approach to groundwater discharges, the linear reservoir assumption, subject to incorporating recharge into the analysis, can suitably model the groundwater behaviour in many catchments (Chapman, 1999). Where the groundwater behaviour cannot be adequately modelled with a linear reservoir assumption, a non-linear model should be used. Eq. (1) is shown to be the special case solution of the generalised non-linear reservoir (Coutagne, 1948):

$$Q_t = Q_0[1 + (n-1)t/\tau_0]^{-n/(n-1)} \qquad (4)$$

where $\tau_0 = S_0/Q_0$ is the turnover time at time zero and n is the measure of the non–linearity of the reservoir.

Another approach to modelling this situation with a linear reservoir is to split the non-linear reservoir into a number of smaller reservoirs in parallel that could each be modelled as being linear (Tallaksen, 1995). This is the approach taken in this paper for calculating the τ related to each of the reservoirs that represent the subsurface pathways. In this case the hydrograph recession is modelled by the superposition of four individual reservoirs, one for each pathway:

$$Q_* = Q_0 e^{-t/\tau^*} = Q_{0O} e^{-t/\tau_O} Q_{0I} e^{-t/\tau_I} + Q_{0S} e^{-t/\tau_S} + Q_{0D} e^{-t/\tau_D} \quad (5)$$

where $*$,$_O$ $_I$, $_S$, and $_D$ refer to combined, overland, interflow, shallow and deep groundwater storages respectively.

In order to identify these τ values for each of the pathways present, Master Recession Curves (MRC) are constructed. This is achieved by plotting many recessions side by side, as per the tabulation method (Johnson et al., 1956). Analysis of the MRC allows the characteristic response of a catchment at different discharge levels to be inferred from the rate of recession of the discharges.

3.2 Recursive digital filters

This technique is based upon a recursive digital filter commonly applied in signal analysis and processing. The basis of this method is that filtering out high-frequency signals is analogous to the separation of 'low-frequency' slow response flow from high-frequency quick response flow. The main drawback of this method is that the selection of parameters can be subjective (though not always) and physically unrealistic.

Three types of recursive digital filters are compared to each other. These are the 'one-parameter', and two different 'two-parameter' algorithms.

3.2.1 <u>One Parameter</u>

The first 'one-parameter' algorithm (Lyne and Hollick, 1979) was shown to maintain baseflow at a constant value once overland flow had ceased and hence updated (Chapman and Maxwell, 1996) to a form that has the groundwater flow being a simple weighted average of the quick response flow and the slow response flow at the previous time interval:

$$Q_{St} = \frac{k}{2-k} Q_{St-1} + \frac{1-k}{2-k} Q_t \qquad (6)$$

subject to the condition that

$$Q_{St} \le Q_t \qquad (6a)$$

where Q_S is slow response flow (L^3/T), Q is streamflow (L^3/T), k is the recession constant and t is the time step.

3.2.2 Two Parameter

The most widely used 'two-parameter' algorithm, the Boughton-two-parameter algorithm (Boughton, 1993) was developed from the 'one-parameter' algorithm. It replaces $(1-k)$ with C to add another degree of flexibility to the algorithm. Equation 6 becomes:

$$Q_{St} = \frac{k}{1+C} Q_{St-1} + \frac{C}{1+C} Q_t \qquad (8)$$

again subject to Equation (6a).

The addition of parameter C, although allowing the algorithm to be more flexible, reduces its objectivity as C must be chosen by the user of the algorithm. If an optimisation programme is implemented to select a value for C, this parameter C will be increased until the entire streamflow that is observed, derives from groundwater flow. Therefore C should be selected with the objective of achieving the correct point for quick response flow to end on the hydrograph.

Eckhardt (2005) developed a two-parameter filter in an attempt to remove the subjectivity of C parameter from Boughton's algorithm. This algorithm assumes there is an initial knowledge of the catchment, or at least a surrogate catchment, which would provide an estimate of the maximum baseflow index (BFI_{max}), the ratio of baseflow (slow response pathways) to total streamflow.

$$Q_{St-1} = \frac{1-BFI_{max}}{1-kBFI_{max}} kQ_{St-1} + \frac{1-k}{1-kBFI_{max}} BFI_{max} Q_t \qquad (9)$$

This is again subject to Equation (6a).

This algorithm also involves a subjective parameter in that BFI_{max} cannot be measured *a priori*. Therefore, there will be an element of calibration involved in applying the filter that will require the updating of the BFI_{max} value until a satisfactory separation is computed.

The Bougthon-two-parameter algorithm has been shown to be more effective than the 'one-parameter' algorithm (Chapman, 1999) and due to its widespread use and ease of implementation, it was applied in this study. Eckhardt's algorithm was also used for comparison with Boughton's algorithm.

3.3 Fixed and sliding interval, and local minima turning point separation methods

Three methods, two of which are available in the HYSEP model (Sloto and Crouse, 1996), while the third is a modified version of a third method available in HYSEP, were used for calculating BFI from discharge data. These methods are the fixed interval method, the sliding interval method and the local minima turning point method. These methods provide a consistent and automated technique that can separate the hydrograph into quick and slow response flow.

The fixed and sliding interval methods are contained within the HYSEP, a hydrograph separation model from the United States Geological Survey (USGS) that estimates the base flow component of streamflow. These two methods were both developed by Pettyjohn and Henning (1979). The fixed interval method involves identifying the minimum discharge within an interval and setting it as the baseflow for that interval. The sliding interval method is analogous to the fixed interval method, but the interval moves forward in the discharge series by one time step each time, with the minimum value of the interval being set as the value of baseflow at the median of the interval.

The local minimum turning point technique (Institute of Hydrology, 1980) involves the use of the fixed interval method to identify local minima in each non-intersecting interval. The minimum of each interval is then compared to two neighbouring minima to establish if it is less than 90% of these values. If it is, these minima are termed turning points, which are then connected to define the baseflow series.

The interval in each of these methods is calculated from the approximation for the time from the peak of an event to the end of quickflow (Linsley et al., 1949):

$$N = 0.83A^{0.2} \qquad (10)$$

where A is the catchment area in km^2. The interval is calculated as being twice this time. N = 2.5 days is also a commonly chosen value (Institute of Hydrology, 1980). The output of the local minima turning point method is compared, calculating N with both methods. The choice of the time base N has a large effect on the BFI calculated, as the minimum value chosen for separations is sensitive to this N value (Misstear and Fitzsimons, 2007).

3.4 Recharge coefficients

Recharge to aquifers can be estimated by calculating effective rainfall, using a soil moisture budget technique, and then multiplying by recharge coefficients to indicate the proportion of effective rainfall contributing to groundwater recharge (Misstear et al., 2009). Table 3 describes the hydrological setting relating to each recharge coefficient and the range over which these coefficients tend to vary. These recharge coefficients are identified from soil and subsoil GIS data for the catchment in conjunction with a recharge coefficient table (Hunter Williams et al., 2012 (In Press)).

Table 3

Effective rainfall is calculated as total rainfall less actual evapotranspiration. Actual evapotranspiration is estimated from recorded values of potential evapotranspiration and a soil moisture budgeting approach such as the FAO Penman-Monteith method (Allen et al., 1998). As previously mentioned, aquifers in Ireland have been rated from regionally important, to locally important, to poor. Due to the low storativity characteristics of many aquifer types, there is a limit to the amount of recharge that can be accepted by the aquifer. A cap on the amount of recharge is defined for the locally important and poorly productive and aquifers: 200 mm/yr for locally important aquifers and 100 mm/yr in poor aquifers (Working Group on Groundwater, 2005). GIS shapefiles for subsoil, soil and aquifer mapping from the Geological Survey of Ireland, and rainfall and evapotranspiration data, collected from the study site, were utilised to calculate the recharge coefficients. The soil and subsoil shapefiles indicate the permeability of the overburden above the aquifer, while the aquifer shapefile defines the productivity class of the aquifer and thus if it is limited in the recharge it may receive. The vulnerability shapefiles, derived from mapping carried out to rate the risk of contaminants entering the aquifers, are also informative as the approach used to develop these is analogous to the method required for calculating the recharge coefficients. The recharge coefficient approach therefore provides a basis for separating the quicker response pathways (conceptually overland flow and interflow) from the slower response pathways (shallow and deep groundwater).

3.5 Hydrological Modelling

Hydrological models can help to inform the decisions of catchment and river basin managers, though they are not solely decision making tools, but are part of the investigation process. Hydrological modelling in this research was carried out with the NAM model, as described below.

3.5.1 NAM

The Danish "Nedbør-Afstrømnings-Model", literally meaning rainfall runoff model, was developed in 1973 by the Department of Hydrodynamics and Water Resources at the Technical University of Denmark (Nielsen and Hansen, 1973). It is a deterministic, lumped, conceptual rainfall–runoff model for simulating the hydrological cycle.

NAM was applied in Ireland in many catchments as part of a previous study concerned with groundwater-surface water interactions (RPS, 2008). The conceptual model followed was a simpler three-pathway (overland, intermediate and groundwater) model compared with the four-pathway conceptual model of this paper. Also, the previous study did not involve detailed catchment studies to help validate the model results. Building upon this work, NAM is considered to be a very useful tool in catchment modelling in the Irish setting. It has the capacity to simulate the four pathways of the conceptual model, while the model's lumped approach does not require complex detailed input data (which is generally not available for most catchments). This lumped approach also has the flexibility to be adapted to the variable geological settings encountered in Ireland.

The NAM model represents the various hydrograph components using a moisture budgeting approach for different storages. The storages behave much like the linear reservoirs described by Equation 1. The form of model structure which was applied in this research involved four storages: snow storage was omitted and the lower storage was split into two storages, one for shallow and one for deep groundwater. Overland flow and interflow were modelled as discharges from the uppermost storage; interflow was modelled as discharge from the bottom of this storage; while overland flow was overtopping discharge from this storage analogous to saturation excess flow. A middle storage monitored soil moisture deficit in the catchment and acted as a control for overland flow, interflow and recharge occurrence. The NAM structure is shown in Figure 3.

Figure 3

4 Results

4.1 Master Recession Curve Analysis

Employing the recession analysis methods, Master Recession Curves were constructed for the study catchments. It was assumed that the two faster responding equations (those with the two steepest recessions) fitted to the data were the overland flow and interflow pathways, with the two slowest responding equations the shallow and deep groundwater pathways. The recession constants were then identified from each of the equations for these recession segments as previously outlined in Section 3.1. These were then applied to calculate cumulative storage of water in each of the pathway reservoirs. These cumulative storages were utilised to provide initial indications of the proportion of the hydrograph derived from each pathway. An example of one such MRC is shown in Figure 4, with the black arrows identifying the equations that relate to the fitted recession slopes, while results of all the catchments are shown in Table 4.

Figure 4

Table 4

4.2 Recursive digital filters

Following on from the identification of the recession constants identified in the recession analysis, the Boughton two-parameter and Eckhardt digital filter methods were applied. These were calibrated until the five criteria outlined previously had been satisfied adequately. This was achieved manually by adjusting the *C* parameter for the Boughton algorithm and the BFI_{max} parameter for the Eckhart algorithm, while visually inspecting the hydrograph separations, while assessing the BFI obtained. An example of a separation obtained for quick and slow response pathways in the Blackwater Fyanstown catchment is presented in Figure 5. Table 5 contains the BFI values computed for the catchment using the 'best' calibrations for the Boughton and Eckhardt algorithms This was based on BFI calculated from the MRC analysis, the recharge coefficient approach and NAM modelling, as well as a qualitative assessment of geological conditions.

Figure 5

Table 5

4.3 Recharge coefficients

The recharge coefficients were calculated for the catchments by examining the GIS layers for soil, subsoil and aquifer type. An example of the GIS data applied to calculate these coefficients for the Mattock catchment are presented in Figure 6. The area of each soil and subsoil type, with reference to Table 3, allowed the recharge coefficient to be calculated for each soil and subsoil combination with the overall catchment recharge coefficient computed from the average of these, weighted by area. These coefficients were then assessed in conjunction with hydrologically effective precipitation (rainfall – actual evapotranspiration) to calculate the annual BFI for the study catchments. Table 7 displays the BFI values calculated applying this approach, with the mean values for the recharge coefficients taken from the recharge coefficient table (Table 3).

Figure 6

4.4 Fixed and sliding interval, and local minima turning point separation methods

The two HYSEP filters and the local minima turning point method were also applied to the study catchments. The standard interval (2*N*) for the local minima turning point method is 5 days, which was adopted, but the interval was also calculated from Equation 10. Table 7 includes the BFI values obtained using three filter methods for the study catchments, with two values for BFI calculated for the local minima turning point method employing a 5 day interval and calculated interval. Figure 7 illustrates separations using this approach in the Blackwater Fyanstown catchment.

Figure 7

4.5 Hydrological Modelling

Finally, NAM was applied to the catchments, with model parameters initially selected based on guidance from the user manual, MRC recession constants for estimates of time constants within the model and from previous studies implementing the model ((Shamsudin and Hashim, 2007; RPS, 2008). Following this, observed discharge assisted with the calibration of these model parameters. All models have an element of subjectivity, as depending on what objective functions are applied to assess the performance of the model, different calibrations are obtained. The Nash – Sutcliffe R^2 value (Nash and Sutcliffe, 1970) was utilised to assess the goodness of fit for the simulated against the observed discharge with the R^2 values shown in Table 6. Simulations were carried out using the smallest time step of rainfall data available. This allowed for improved simulation of peaks in quickly responding catchments, particularly those with small BFI values. An example of the simulated groundwater pathways in the Blackwater catchment are shown in Figure 8. The results of NAM modelling are also presented in Table 6 and Table 7.

Figure 8

Table 6

Table 7

5 Discussion

Table 7 shows that there are large variations in estimates of BFIs obtained by applying the different separation techniques. Even within some of the techniques there is much subjectivity depending on what parameters are chosen and how the final separations are selected as being the most appropriate. Overall it is observed that those catchments with higher BFI values correspond to the catchments with more productive aquifers underlying the soils and subsoils of which they are predominately derived. This is evident in the case of the Nuenna (Monument), which is underlain by a regionally important aquifer with diffuse karst preset. The Nuenna (Monument) has a NAM BFI value greater than 0.87, which when compared with the Glen Burn (Outlet) catchment, underlain by a poorly productive aquifer with a NAM BFI of less than 0.13, emphasises the importance of the aquifer classification within a catchment.

The MRC analysis carried out for each catchment provides an initial estimate of the relative proportions of flow along each pathway within a catchment. These proportions are based upon the assumption of each behaving like a linear reservoir, which is deemed less appropriate for the quicker responding overland flow and interflow pathways. Of importance also, is the calculation of the recession parameter τ for the slower pathways. The τ is computed from the equations fitted to the recessions; these equations are fitted manually. This τ value is used to calculate the value of k for the Boughton and Eckhardt algorithms, but also provides an estimate of the time constant in NAM for the groundwater pathways. Figure 4 provides an example of the MRC tabulation method for the Blackwater Fyanstown catchment. This demonstrates that the slope of each segment corresponds to a different pathway; the slowest responding pathway corresponds with the smallest τ value, while the next smallest τ corresponds to a superposition of the two slowest responding pathways.

The fixed interval, sliding interval and local minima turning point techniques appear to be the least subjective, although there is some doubt as to whether it is better to calculate the interval ($2N$), using Equation 10, or implement a predefined value of 5 days. As catchment size decreases to the point where the N calculation provides an interval of less than 5 days; this results in the choice of the lower N value giving a higher BFI value. While Equation 10 provides an objective means of calculating which N to use, experience is required to select the N that will provide a BFI value that is compatible with the recharge coefficients approach. An alternative to using Equation 10, is to assess the response of the groundwater levels within a borehole located close to the river being studied (Misstear and Fitzsimons, 2007). The N value is selected to match the rising and falling response of the water level measured within the borehole. This provides a more realistic shape for the separation but may not fully address the overestimation of the BFI, as this method still requires the turning points to be on the hydrograph to define the location of baseflow. This results in the selection of turning points during rainfall events that are much higher than would be plausible. This occurs during the peaks in 1992, 1993 and 1994 in Figure 7, resulting in baseflow contributions in excess of what would be considered feasible. Also if few turning points are identified, the baseflow may be defined as a straight line over a long period, set to the observed discharge in locations where the baseflow is defined as being greater than observed discharge by this straight line. This occurs in 1995 in Figure 7 when the baseflow contribution is low compared with the other years. In this case no turning point was identified during the series of peaks at the beginning of 1995. As a result the baseflow is defined by a turning point during the start of 1994 and in late 1995. If a smaller interval than the 5 days was applied in the analysis, a turning point may have been identified during this period, redefining the baseflow contribution. This lack of turning points influences only the local minima turning point technique, but the overestimation caused by choosing baseflow values from the observed discharge affects all three of these methods.

Upon inspecting Figure 7, it is clear that the separations from the fixed interval, sliding interval and local minima turning point techniques appear unrealistic when set against the five requirements of baseflow outlined in the introduction to this paper. It is also observed in Figure 7, that both the sliding and fixed interval techniques follow the shape of the hydrograph with no recession observed after an event occurs. While the local minima turning point method provides lower estimates of baseflow, the separated baseflow fails to continue to recede after the event begins. Additionally, the peak of the baseflow always occurs as it rejoins the hydrograph, rather than peaking after the event peak, then rejoining the hydrograph following an exponential recession thereafter.

The Boughton and Eckhardt algorithms, however, do satisfy these requirements. In Figure 5, it is observed that recessions occur for a short period after the event has begun, with (though not always) the peak of the baseflow occurring after the peak of the hydrograph, followed by an exponential recession until the baseflow rejoins with the hydrograph. However, the application of these methods relies on the operator having a previous estimate of BFI. Although the *k* value can be informed from MRC analysis, having the effect of reducing the independence of this separation method, the remaining *C* parameter in the Boughton algorithm and the BFI_{max} parameter in the Eckhardt algorithm are free variables which are very sensitive in relation to the BFI value calculated. While the *C* parameter is based originally on having a value of *1-k*, this additional *C* parameter is employed as a 'free variable' that can be adjusted as necessary to obtain the baseflow separation required. This *C* parameter is therefore disconnected from its *1- k* origins and as such is picked from subjective experience, making it difficult to replicate the separation obtained. The BFI_{max} parameter, however, has an almost complete control over the value of BFI as can be seen from Table 8, where two catchments where chosen, Nuenna (Monument) with a very high BFI and Glen Burn catchment with a low BFI for Irish conditions. It is evident here that the subjective choice of BFI_{max} almost completely defines BFI, whereas the *k* value has almost no influence on overall volume but will affect the baseflow shape. This results in the user of the algorithm needing to know the BFI of the catchment in advance, and also to have an idea of the baseflow hydrograph shape. Nevertheless, these algorithms are useful for obtaining separations of time series data that have exponential recessions with BFI values based on prior knowledge. Thus, they are of more value for understanding baseflow distribution in the hydrograph, rather than inferring BFI values.

Table 8

An examination of the BFI values calculated using the different approaches, presented in Table 7, allows the variation in BFI between methods to be evaluated. The recharge coefficients approach provides a physically-based framework within which to make initial estimates of BFI based on the depth to bedrock and the permeability of the overburden. This is therefore viewed as a guiding BFI value for the amount of water feeding into the groundwater pathways. This groundwater, conceptually, is thus observed as maintaining baseflow. By choosing the mean value for recharge coefficients from Table 3, the subjectivity of the computed separations is minimised. Adopting this as starting point in the appraisal of the different methods it would appear that the HYSEP methods and the local minima turning point method, consistently overestimate the BFI value. The Master Recession Curve tabulation method tends to provide a reasonable initial estimate for BFI calculation, analogous to the recharge coefficient approach. Unlike the recharge coefficient approach, the MRC uses streamflow data to identify general characteristics of a catchment by observing trends in recessions following rainfall events. Due to this analysis of streamflow, rather than just geological unit analysis, the MRC approach estimates the flows in catchments with significant karst-derived groundwater inputs (i.e. the Deel and the Nuenna) with more success, as typical karst features such as swallow holes and conduits have significant impacts on hydrology across a wider spectrum of the observed streamflows. The subjectivity of the formation of the MRC and identifying the breaks in slope of the MRC are of concern, but when applied in conjunction with the recharge coefficient approach and NAM, it provides a useful way of informing the recession parameter of the Boughton and Eckhardt algorithms. NAM is employed both as a validation method, but also as a means of investigation in itself as optimisation methods may suggest that the conceptual model of a catchment is incorrect if very different BFI values are obtained. In this manner the iterative nature of calculating the BFI value for the different catchments should be appreciated.

6 Conclusions

The calculation of the Baseflow Index of a catchment is both a difficult and subjective task due to the inability of current technology to measure baseflow contributions accurately on a catchment scale. After implementing many different hydrograph separation techniques and applying the NAM modelling as a means of investigating the contribution of pathways to the river hydrograph, the Master Recession Curve analysis, the recharge coefficient approach and the NAM modelling are identified as providing an integrated approach for calculating the Baseflow Index (BFI). This integrated approach put forward in this paper provides the framework for calculating a reliable BFI, generally within a small range, which is consistent with discharge data and the geological setting of the catchment in question. The Master Recession Curve approach of identifying all the responses present and not just a quick and slow response allows the baseflow to be identified with more confidence. The recharge coefficients method indicates the contribution of effective rainfall to quick response and groundwater pathways taking account of the geological setting of the catchment, though may struggle with recharge that may occur in karst settings due to features such as swallow holes recharging the aquifer with surface runoff. The hydrological pathway modelling using NAM then allows the checking of the viability of the conceptual separations. This modelling also provides a means of investigation of what type of separation is possible with the rainfall and evapotranspiration data available.

This integrated approach therefore brings together the rainfall input to the catchment, the geological setting of the catchment and the catchment outputs of discharge measured in the river and evapotranspiration, thereby providing a more reliable BFI value than one based on a single approach. The Boughton and Eckhardt methods do not necessarily provide a reliable BFI value estimate due to their subjectivity, but are a useful means of obtaining a baseflow time series that satisfies the five objectives of baseflow separation outlined in Section 1. The HYSEP and local minima turning point techniques, while providing feasible BFI values if a suitable interval is chosen, do not provide reliable baseflow hydrographs when applied on their own.

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Figure 1. Pathways present in poorly productive and productive aquifers on the left and right respectively (J Deakin 2012: after N. Hunter-Williams and D. Daly)

Figure 2. Study catchment locations.

Figure 3. NAM structure schematic

Figure 4. Master Recession Curve, Tabulation Method for Blackwater (Kells) Fyanstown .

Figure 5. Boughton and Eckhardt baseflow separations for Blackwater Fyanstown.

Figure 6. Mattock soils and subsoils GIS data.

Figure 7. Fixed and Sliding Interval, and Smoothed Minima Turning Point methods for Blackwater Fyanstown.

Figure 8. NAM modelled groundwater pathways for Blackwater.

Table 1. Irish aquifer classifications (DELG/EPA/GSI, 1999).

Rf	Regionally Important Aquifer - Fissured bedrock
Rk	Regionally Important Aquifer - Karstified
Rkd	Regionally Important Aquifer - Karstified (diffuse)
Rkc	Regionally Important Aquifer - Karstified (conduit)
Lm	Locally Important Aquifer - Moderately productive
Lk	Locally Important Aquifer - Karstified
Ll	Locally Important Aquifer - Moderately productive only in local zones
Pl	Poor Aquifer - Unproductive except in local zones
Pu	Poor Aquifer - Generally unproductive

Table 2. Study catchment characteristics.

Catchment	Area	Catchment Descriptors				
		Land Use	Aquifer Classification	Annual Rainfall	Annual Evapotranspiration	Runoff
	km^2	**Type (%)**	**Type (%)**	**mm**	**Mm**	**mm**
Deel	283.1	Pasture (78.6)	Ll (88.1)	973	481	492
Blackwater (Kells)	699	Pasture (80.1)	Pl (74.1)	1026	491	535
Fyanstown	187.6	Pasture (86.5)	Ll (34.7), Pl (59.7)	1020	476	545
Owenshree	34.5	Pasture (41.1) Peat (27.9)	Pl (75.7)	1501	530	971
Ballycahalan	47.7	Forest (37.5) Peat (31.6)	Pl (85)	1501	530	971
Mattock	11.6	Pasture (84.6)	Pl (92.3)	885	460	425
Nuenna (Rocky)	21.6	Pasture (83)	Rkd (84.2)	1026	485	541
Nuenna (Monument)	34.99	Pasture (87)	Rkd (81.4)	985	485	500
Glen Burn	5	Pasture (100)	Pl (100)	843	460	383

Table 3. Recharge coefficients for different hydrogeological settings adapted from Hunter Williams et al., (2012 (In Press)).

Vulnerability category	**Hydrogeological setting**		**Recharge coefficient (RC)** *Min (%)*	*Inner Range*	*Max (%)*
Extreme	1.i	Areas where rock is at ground surface	30	80-90	100
	1.ii	Sand/gravel overlain by 'well drained' soil	50	80-90	100
	1.iii	Sand/gravel overlain by 'poorly drained' (gley) soil	15	35-50	70
	1.iv	Till overlain by 'well drained' soil	45	50-70	80
	1.v	Till overlain by 'poorly drained' (gley) soil	5	15-30	50
	1.vi	Sand/ gravel aquifer where the water table is ≤ 3 m below surface	50	80-90	100
	1.vii	Peat	1	15-30	50
High	2.i	Sand/gravel aquifer, overlain by 'well drained' soil	50	80-90	100
	2.ii	High permeability subsoil (sand/gravel) overlain by 'well drained' soil	50	80-90	100
	2.iii	High permeability subsoil (sand/gravel) overlain by 'poorly drained' soil	15	35-50	70
	2.iv	Sand/gravel aquifer, overlain by 'poorly drained' soil	15	35-50	70
	2.v	Moderate permeability subsoil overlain by 'well drained' soil	35	50-70	80
	2.vi	Moderate permeability subsoil overlain by 'poorly drained' (gley) soil	10	15-30	50
	2.vii	Low permeability subsoil	1	20-30	40
	2.viii	Peat	1	5-15	20
Moderate	3.i	Moderate permeability subsoil and overlain by 'well drained' soil	35	50-70	80
	3.ii	Moderate permeability subsoil and overlain by 'poorly drained' (gley) soil	10	15-30	50
	3.iii	Low permeability subsoil	1	10-20	30
	3.iv	Peat	1	3-5	10
Low	4.i	Low permeability subsoil	1	5-10	20
	4.ii	Basin peat	1	3-5	10
High to Low	5.i	High predicted permeability subsoils (Sand/gravels)	30	80-90	100
	5.ii	Moderate permeability subsoil overlain by well drained soils	35	50-70	80
	5.iii	Moderate permeability subsoils overlain by poorly drained soils	10	15-30	50
	5.iv	Low permeability subsoil	1	5-10	20
	5.v	Peat	1	5	20

Table 4. Master Recession Curve analysis with flow apportioned to each pathway.

Catchment	Area	Master Recession Curve, Tabulation Method			
		Groundwater Shallow	Groundwater Deep	Interflow	Overlandflow
	km^2				
Deel	283.1	0.296	0.114	0.148	0.442
Blackwater (Kells)	699	0.117	0.148	0.477	0.258
Fyanstown	187.6	0.192	0.037	0.1	0.671
Owenshree	34.5	0.196		0.148	0.142
Ballycahalan	47.7	0.212		0.333	0.455
Glen Burn	5	0.117	0.104	0.437	0.341
Mattock	11.6	0.147	0.073	0.254	0.526
Nuenna (Rocky)	21.6	0.563	0.319	0.1	0.018
Nuenna (Monument)	34.99	0.441	0.357	0.141	0.06

Table 5. Boughton and Eckhardt BFI and parameter values.

Catchment	**Area**	**Calculated BFI**				
		K (parameter)	C (parameter)	Boughton (Calculated BFI)	BFI_{max} (parameter)	Eckhardt (calculated BFI)
	km^2					
Deel	283.1	0.983	0.022	0.559	0.56	0.561
Blackwater (Kells)	699	0.964	0.012	0.25	0.25	0.251
Fyanstown	187.6	0.979	0.006	0.222	0.22	0.22
Owenshree	34.5	0.997	0.004	0.141	0.14	0.14
Ballycahalan	47.7	0.995	0.001	0.166	0.166	0.165
Glen Burn	5	0.98	0.0032	0.14	0.14	0.142
Mattock	11.6	0.991	0.0025	0.218	0.22	0.221
Nuenna (Rocky)	21.6	0.999	0.006	0.859	0.86	0.86
Nuenna (Monument)	34.99	0.999	0.005	0.835	0.835	0.837

Table 6. NAM pathway separations.

<table>
<tr><th>Catchment</th><th>Area</th><th colspan="5">NAM</th></tr>
<tr><td></td><td>km^2</td><td>Groundwater Shallow</td><td>Groundwater Deep</td><td>Interflow</td><td>Overlandflow</td><td>R^2</td></tr>
<tr><td>Deel</td><td>283.1</td><td>0.383</td><td>0.199</td><td>0.104</td><td>0.315</td><td>0.921</td></tr>
<tr><td>Blackwater (Kells)</td><td>699</td><td>0.124</td><td>0.046</td><td>0.227</td><td>0.604</td><td>0.921</td></tr>
<tr><td>Fyanstown</td><td>187.6</td><td>0.244</td><td>0.056</td><td>0.18</td><td>0.52</td><td>0.803</td></tr>
<tr><td>Owenshree</td><td>34.5</td><td colspan="2">0.136</td><td>0.427</td><td>0.437</td><td>0.846</td></tr>
<tr><td>Ballycahalan</td><td>47.7</td><td colspan="2">0.071</td><td>0.246</td><td>0.683</td><td>0.904</td></tr>
<tr><td>Glen Burn</td><td>5</td><td>0.049</td><td>0.078</td><td>0.436</td><td>0.437</td><td>0.895</td></tr>
<tr><td>Mattock</td><td>11.6</td><td>0.148</td><td>0.106</td><td>0.496</td><td>0.25</td><td>0.848</td></tr>
<tr><td>Nuenna (Rocky)</td><td>21.6</td><td>0.473</td><td>0.37</td><td>0.003</td><td>0.154</td><td>0.958</td></tr>
<tr><td>Nuenna (Monument)</td><td>34.99</td><td>0.472</td><td>0.405</td><td>0.006</td><td>0.116</td><td>0.959</td></tr>
</table>

Table 7. Summary of BFI values using different approaches.

Catchment	Area	Calculated BFI								
		Fixed Interval	Sliding Interval	Local Minima (N computed)	Local Minima (N= 2.5 days)	MRC Tab	Recharge Coeffs	Boughton	Eckhardt	NAM
	km^2									
Deel	283.1	0.871	0.871	0.668	0.668	0.559	0.415	0.575	0.57	0.582
Blackwater (Kells)	699	0.775	0.807	0.517	0.542	0.25	0.204	0.25	0.251	0.17
Fyanstown	187.6	0.667	0.697	0.527	0.542	0.222	0.253	0.222	0.22	0.253
Owenshree	34.5	0.558	0.561	0.334	0.244	0.141	0.145	0.141	0.141	0.136
Ballycahalan	47.7	0.812	0.795	0.764	0.757	0.166	0.167	0.166	0.165	0.071
Glen Burn	5	0.556	0.55	0.344	0.284	0.221	0.189	0.14	0.142	0.127
Mattock	11.6	0.582	0.582	0.522	0.249	0.218	0.351	0.218	0.23	0.254
Nuenna (Rocky)	21.6	0.923	0.924	0.595	0.78	0.859	0.543	0.803	0.802	0.843
Nuenna (Monument)	34.99	0.892	0.893	0.389	0.384	0.835	0.439	0.779	0.835	0.877

Table 8. Response of calculated BFI using varying parameters in Eckhardt algorithm.

Eckhardt BFI					
Nuenna (Monument)			**Glen Burn**		
K	BFI_{max}	BFI	k	BFI_{max}	BFI
0.9990	0.9000	0.901149	0.9990	0.9000	0.904
0.9250	0.1000	0.100237	0.9250	0.1000	0.101
0.9250	0.9000	0.900017	0.9250	0.9000	0.9
0.6000	0.1000	0.100045	0.6000	0.1000	0.1
0.6000	0.9000	0.900004	0.6000	0.9000	0.9
0.1000	0.9000	0.900002	0.1000	0.9000	0.9
0.9250	0.0020	0.002274	0.9250	0.0020	.0026

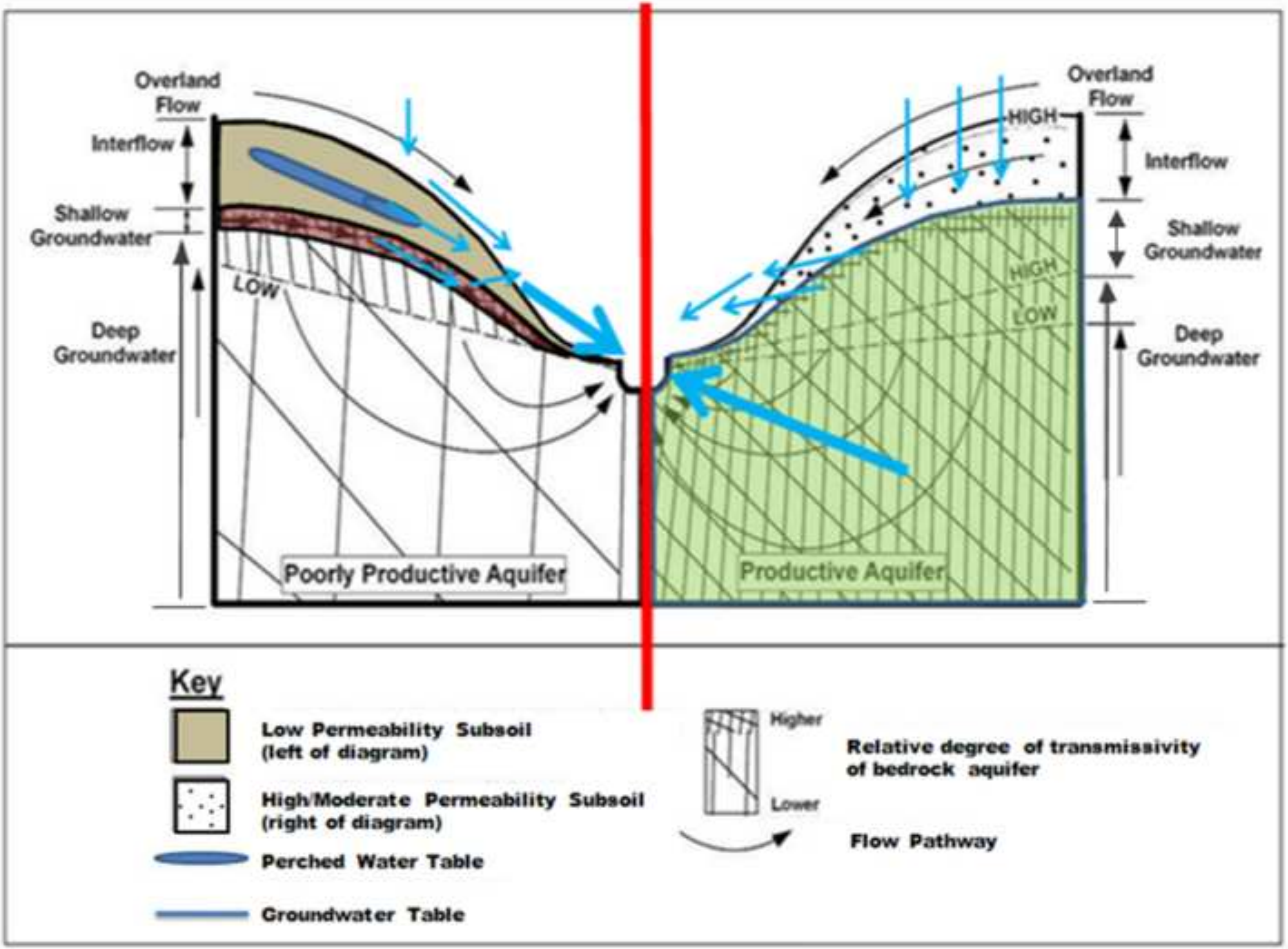

Overland Flow
Interflow
Shallow Groundwater
Deep Groundwater
LOW
Poorly Productive Aquifer
Overland Flow
HIGH
Interflow
Shallow Groundwater
HIGH
LOW
Deep Groundwater
Productive Aquifer
Key
Low Permeability Subsoil (left of diagram)
High/Moderate Permeability Subsoil (right of diagram)
Perched Water Table
Groundwater Table
Higher
Lower
Relative degree of transmissivity of bedrock aquifer
Flow Pathway

Figure 2 Study Catchment Locations

Figure 3 NAM Structure Schematic

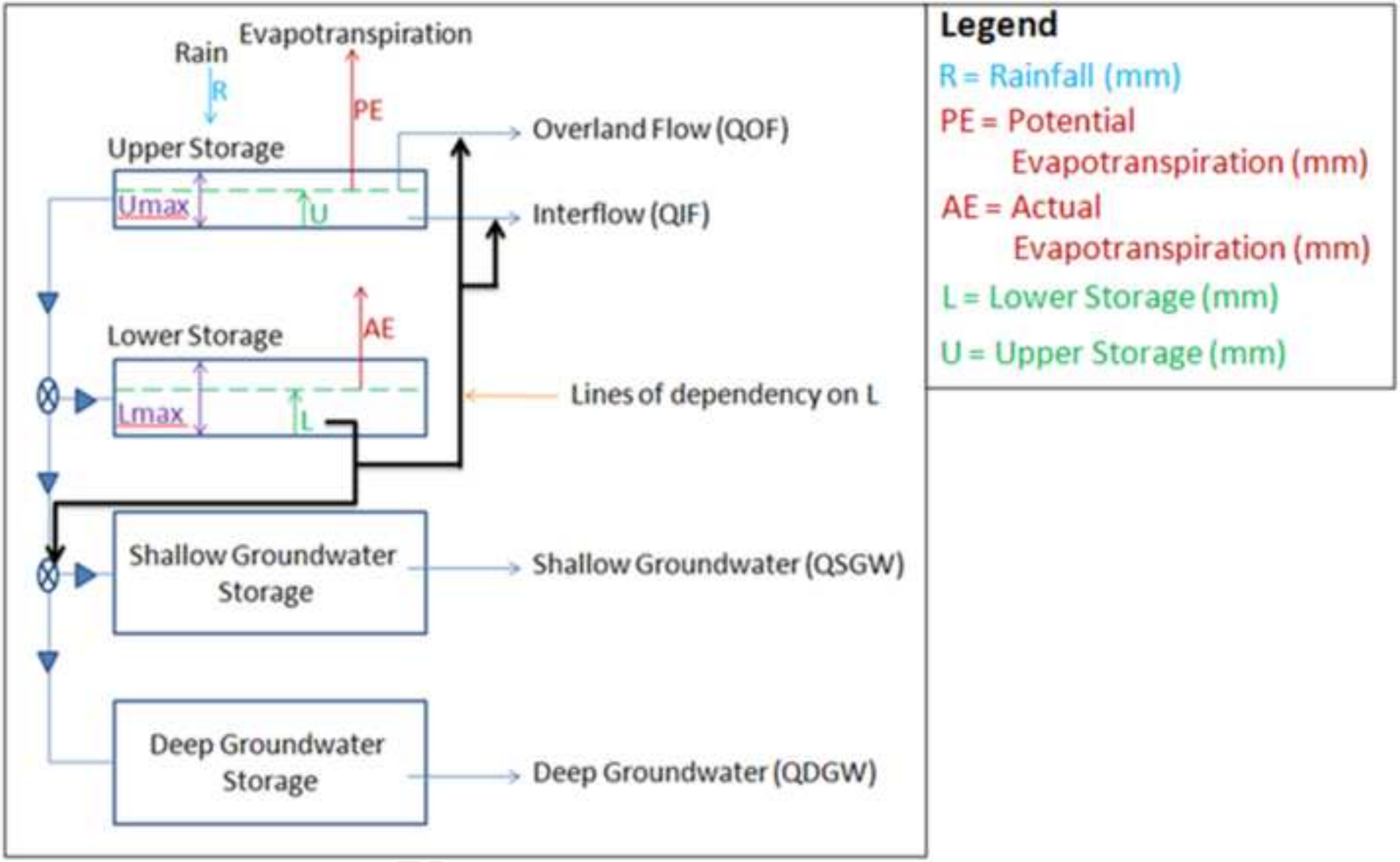


Figure 4 Master Recession Curve

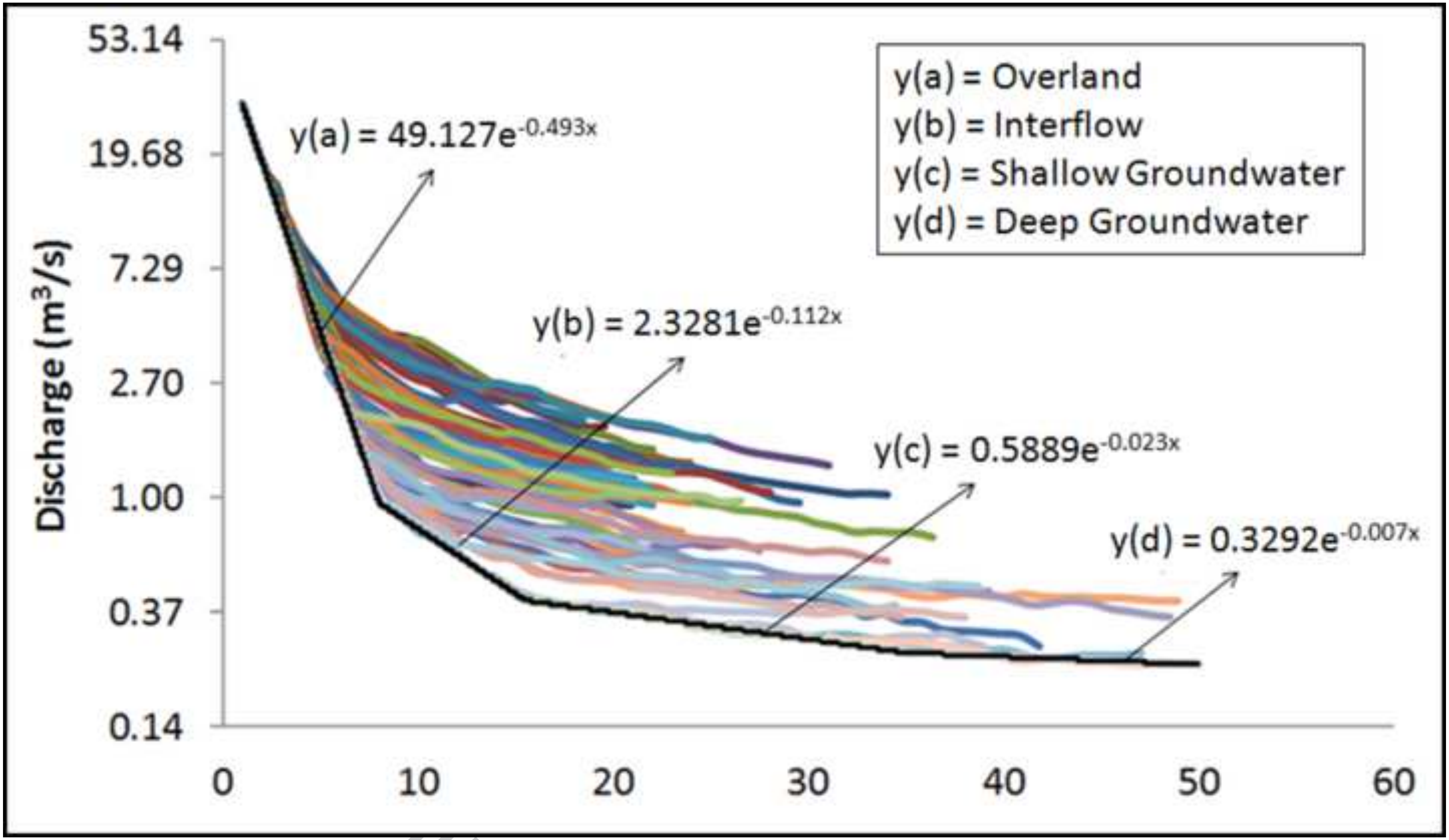


Figure 5 Boughton and Eckhardt Separations

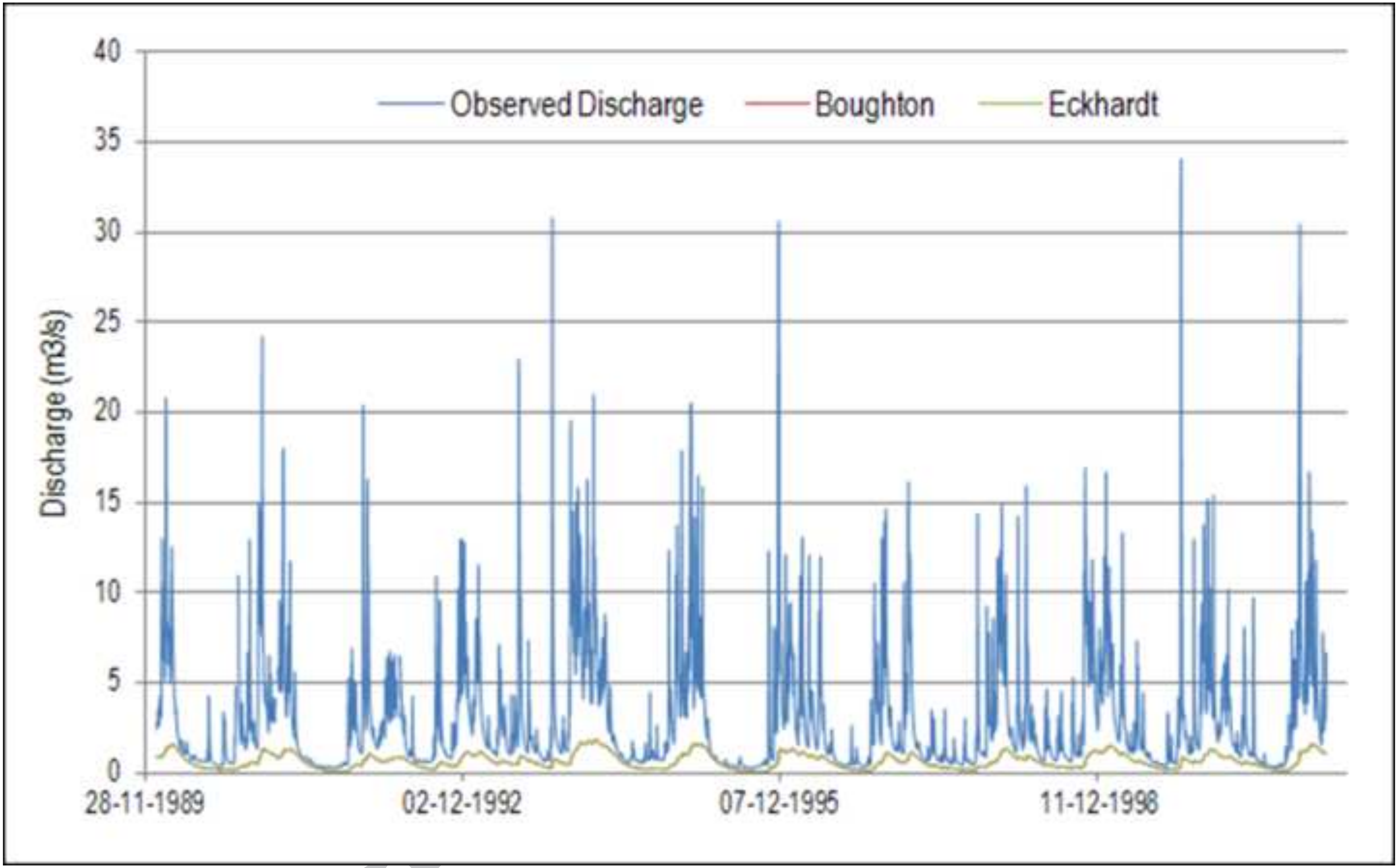


Figure 6 Mattock Soils and Subsoils

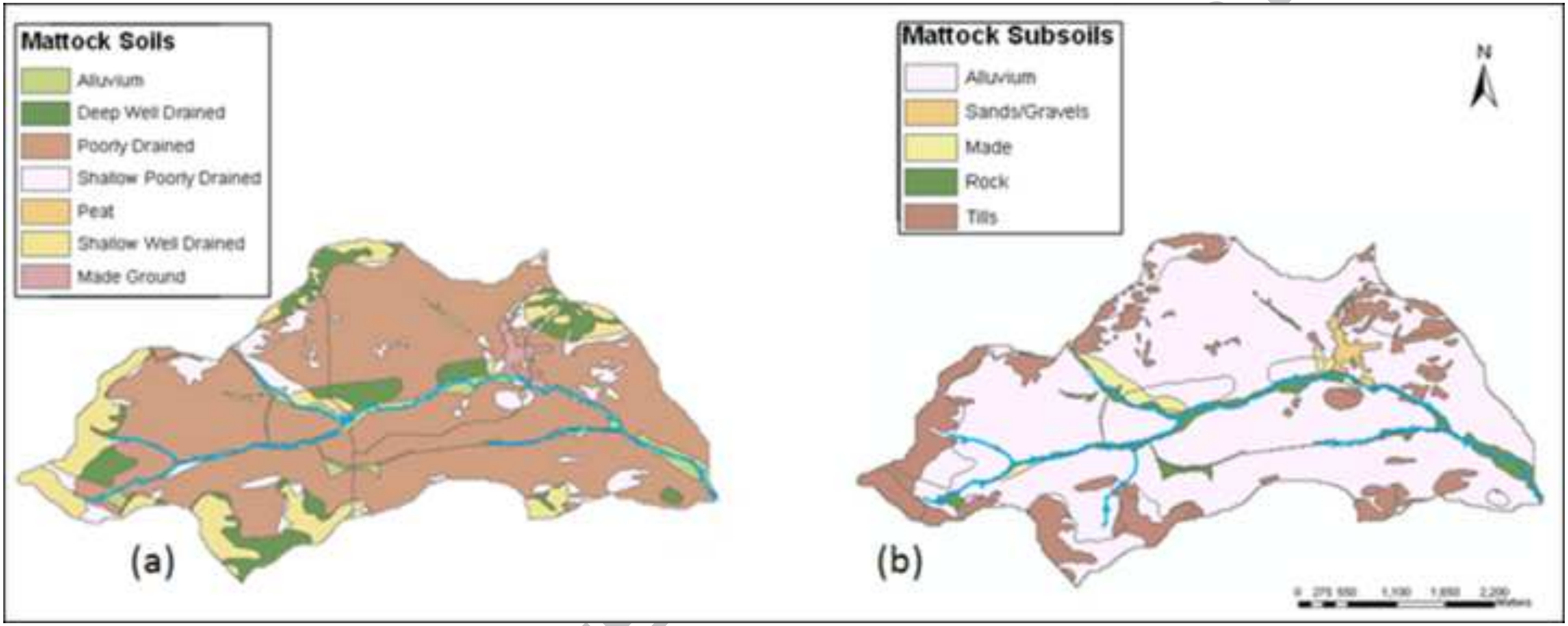


Figure 7 Fixed, Sliding and Turning Point Separations

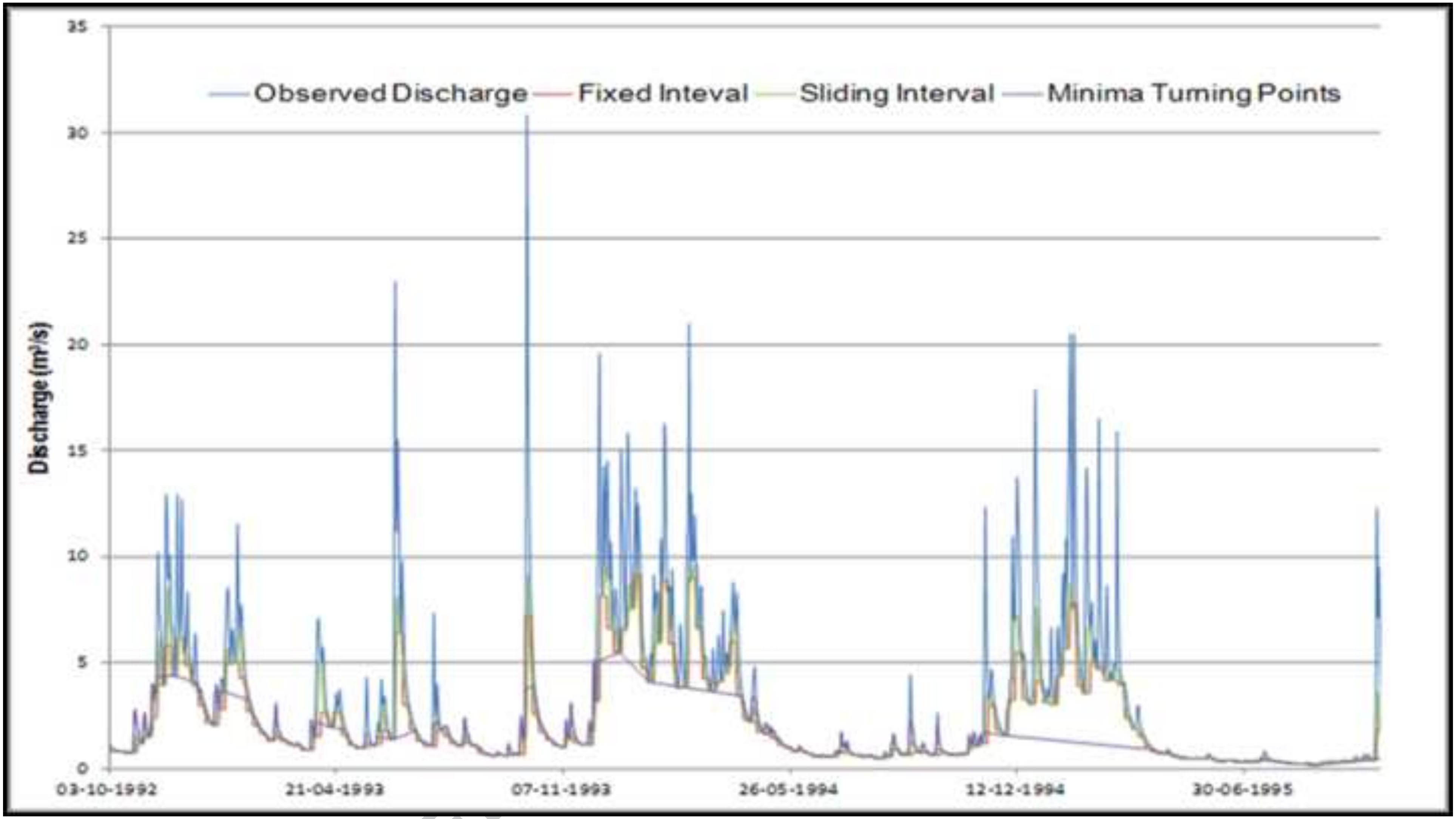
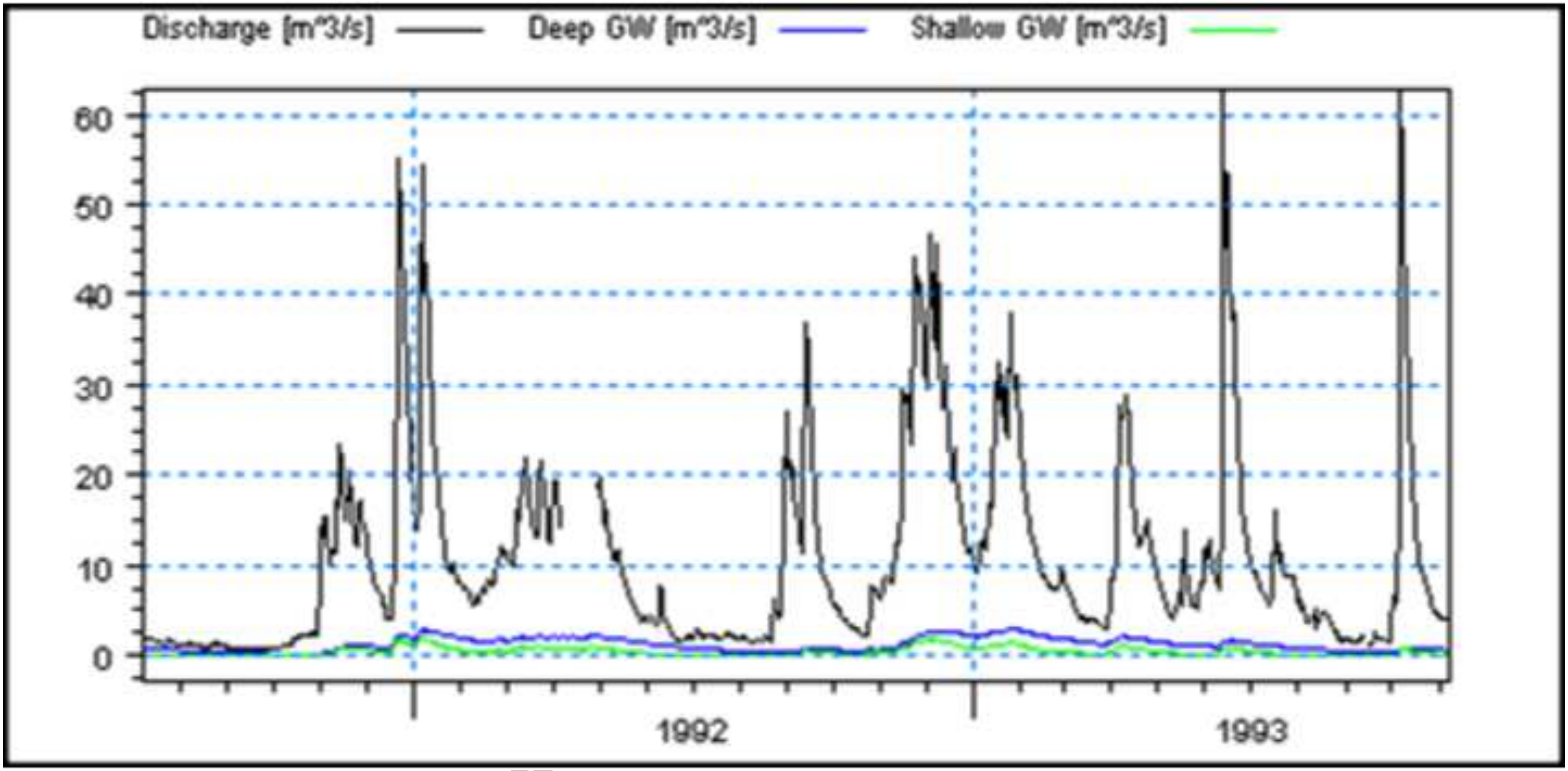


Figure 8 NAM Separations



Highlights

- Outline of novel and objective approach to calculating Base Flow Index (BFI).
- Reliable and repeatable method that can be applied to various geological settings.
- Novel application of Master Recession Curve analysis with NAM lumped model.
- Use of recharge coefficient method, developed in Ireland, to constrain BFI values.